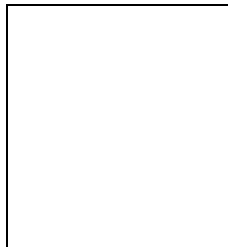


# DETECTION OF COSMIC SHEAR WITH THE WILLIAM HERSCHEL TELESCOPE

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Gravitational lensing by large-scale structure induces weak coherent alignments in the shapes of background galaxies. Here we present evidence for the detection of this ‘cosmic shear’ at the  $3.4\sigma$  significance level with the William Herschel Telescope. Analysis and removal of notable systematic effects, such as shear induced by telescope optics and smearing by tracking and seeing, are conducted in order to recover the physical weak shear signal. Positive results for shear recovery on realistic simulated data are presented, enhancing confidence in the measurement method. The detection of cosmic shear is statistically characterised, and its cosmological significance is discussed.

## 1 Introduction

Understanding the large-scale distribution of matter in the universe continues to be a major issue in modern cosmology. Weak gravitational lensing promises to be a particularly effective method for determining properties of large-scale structure, since it provides direct information concerning the total mass distribution, independently of its state and nature.

The images of distant field galaxies obtained at a telescope are slightly coherently distorted, due to weak lensing by large-scale structure. With extensive measurements of this shear on various scales, one would obtain a direct measure of the power spectrum of density fluctuations along the line of sight.

However, the first stage in such a programme is the detection of the cosmic shear signal; this itself is a challenge, because the rms shear amplitude is small - a few percent on arcminute scales. Recently four papers describing the detection of this effect have been released (Wittman et al 2000, van Waerbeke et al 2000, Bacon et al 2000a, Kaiser et al 2000), presenting mutually consistent results with careful analysis of systematic effects.

Here we overview the detection of cosmic shear obtained with the 4.2m William Herschel Telescope, fully discussed in Bacon, Refregier & Ellis (2000a). The current paper describes the survey strategy, and discusses how the data are analysed to overcome convincingly the contribution of systematic effects to the shear. Simulations used to check our methodology are explained, and the cosmological implications of our results are discussed.

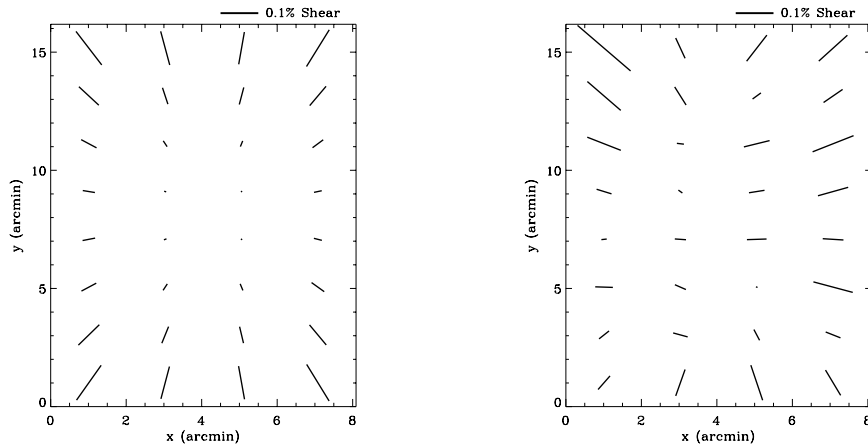


Figure 1: Expected (left) and measured (right) instrumental shear pattern for the WHT Prime Focus. The expected pattern was derived from the distortion model given in the WHT Prime Focus manual (Carter & Bridges 1995). The observed pattern was measured using 3 astrometric frames in one of our fields.

## 2 Observations

The goal of our survey is to obtain a homogeneous sample of deep fields, chosen to be on random lines of sight separated by  $> 5^\circ$  in order to sample independent structures. The galactic latitude of the fields was tuned to afford  $\simeq 200$  stars within the field of view, necessary to correct for anisotropic PSF systematics.

We carried out deep  $R$ -band imaging on 14 such fields with the Prime Focus camera on the WHT. This has an  $8' \times 16'$  field of view and pixel size  $0.237''$ . The fields were exposed for one hour in  $R$ ; median seeing was  $0.81''$ , having excluded exposures with seeing  $> 1.2''$ . We reach a magnitude depth of  $R_{\text{median}} = 25.2$ , with  $R_{\text{median}}$  of 23.4 for our selected sample,  $z_{\text{median}} \simeq 0.8$ , and a number density  $N = 14.3 \text{ arcmin}^{-2}$ .

## 3 Analysis of Systematic Effects

The aim of our analysis is to remove carefully systematic effects from the galaxies' measured ellipticities, leading to unbiased measures of the small ( $\simeq 1\%$ ) mean shear components for each field. We wish to measure the mean shear in  $8' \times 8'$  cells, for increased shear signal and to allow cross-correlation tests.

We used the Kaiser, Squires & Broadhurst (1995) method (KSB) implemented by Kaiser's `imcat` software for object detection and shape measurement. A detection signal-to-noise  $\nu > 15$  limit was imposed on our usable galaxy catalogue to remove correction systematics found at low signal-to-noise level.

The shear induced by telescope optics must be dealt with; by calculating the telescope distortion using objects' relative positions in several dithers, we show that this is negligible (shear due to telescope  $< 0.003$  everywhere; see figure 1).

Next, the PSF anisotropy from e.g. tracking errors must be removed (see figure 2). Before correction this effect induces an rms stellar ellipticity  $e = 0.07$ , but after subtracting a fitted 2-dimensional cubic to stellar ellipticities, the residual stellar rms is a mere  $e = 1.4 \times 10^{-3}$ . We correct the galaxy ellipticities following Luppino & Kaiser (1997), using the stellar fit model and responsivities to smear measured for the galaxies.

Finally, galaxies are corrected for isotropic smear, i.e. the fact that smaller galaxies' shapes have been more affected by seeing-induced circularisation. Again we follow Luppino & Kaiser's (1997) method; this results in estimates for the mean shear components in each  $8' \times 8'$  cell.

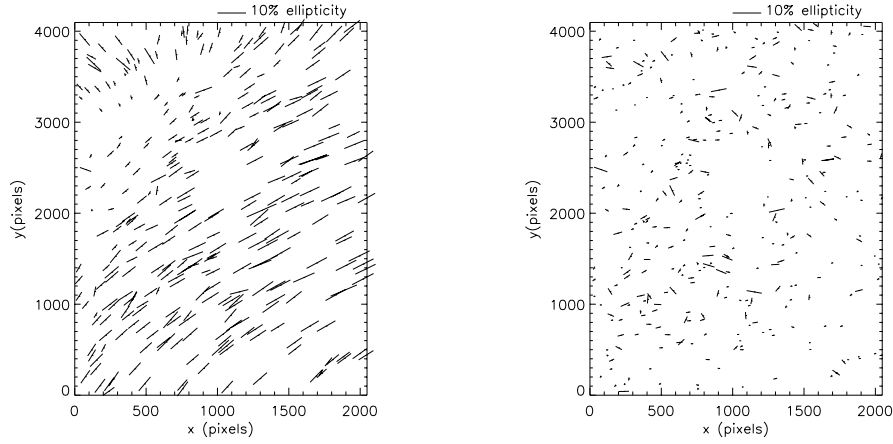


Figure 2: Left: Stellar ellipticity distribution before correction for observed field (CIRS12). Mean value observed  $\bar{e}^* \simeq 0.07$ . Right: Residual stellar ellipticity after correction. The residual mean ellipticity is  $\bar{e}^{res} \simeq 2.6 \times 10^{-3}$ .

#### 4 Shear Measurements on Simulated Data

In order to check our correction of systematics, and to calibrate KSB-measured shear to real shear, we constructed simulated WHT fields on which to carry out the above shear analysis (Bacon et al 2000b); one can apply a chosen shear to a field, and test its recovery by our algorithm. By creating a joint probability model of the magnitude - number density - ellipticity - radius distribution of galaxies in Ebbels' (1998) HST Groth Strip survey catalogue, we were able to draw out statistically similar simulated catalogues for shearing and analysis.

The catalogues were visualised with IRAF artdata; telescope-specific pixelisation, throughput, anisotropic PSF, poisson and readout noise were added. A null set of 20 simulated fields without shear were created, together with a further 30 fields with an rms shear of 1.5%. The KSB analysis described above was carried out on each field.

#### 5 Results

We shall now compare the detection results for the simulated and real data. The left-hand panel of figure 3 shows the mean shear components found for our 1.5% rms shear simulations (30 cells). The inner circle represents the variance that would be expected from noise alone; one can see that there is an excess variance  $\sigma_{\text{lens}}^2$ , which turns out to be significant;  $\sigma_{\text{lens}}^2 = (0.013)^2 \pm (0.006)^2$ , to be compared with our input  $\sigma_{\text{lens}}^2 = (0.015)^2$ . The fact that the method has detected the simulated signal with the correct amplitude is encouraging.

The middle panel of figure 3 shows the mean shear components for 20 simulations with no shear added. Note that here the variance is accounted for by noise alone; as expected, there is no excess variance.

The shear results for our observed fields are shown in the right-hand panel of figure 3. Again we see an excess variance; with a thorough statistical analysis we find this to be significant, with  $\sigma_{\text{lens}}^2 = (0.016)^2 \pm (0.008)^2 \pm (0.005)^2$ , the errors being due to noise and uncertainty on any remaining systematics respectively. This corresponds to a  $3.4\sigma$  detection of cosmic shear.

By comparing our  $\sigma_{\text{lens}}^2 = (0.016)^2 \pm (0.012)^2$  (error now includes cosmic variance) with that expected for popular cosmological models, we find that COBE-normalised SCDM is ruled out at  $3\sigma$  level, whereas cluster-normalised  $\tau$ -,  $\Lambda$ -, and OCDM are highly consistent with the data.

Our results also afford us a measure of  $\sigma_8$  for a given cosmological model. For instance, for  $\Lambda$ CDM with  $\Omega_m = 0.3$ , we obtain  $\sigma_8 = 1.47 \pm 0.51$ , consistent with cluster abundance determinations,  $\sigma_8 = 1.13 \pm 0.19$  (Viana & Liddle 1996).

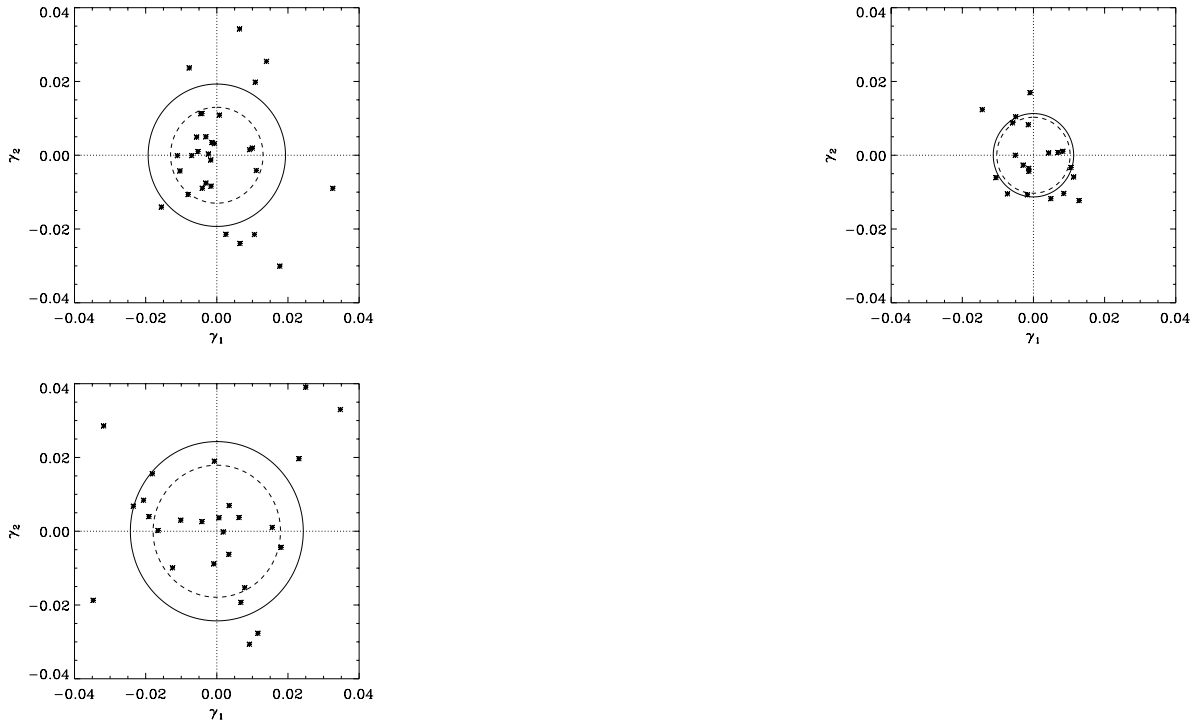


Figure 3: Mean  $\gamma_1$  and  $\gamma_2$  for: (left) 30 simulated cells with rms 1.5% shear; (centre) 20 simulated null cells; (right) 26 observed cells. The dashed circle shows the noise rms, the solid circle shows the total rms. In the null case, the total rms is consistent with noise alone; in the other cases the excess shear variance is significant.

With increased numbers of fields in the future, cosmic shear variance measurements will afford very precise estimates of  $\sigma_8$ , while skewness measurements of the distortion field will provide an independent estimate of  $\Omega_m$ .

## 6 Conclusion

Evidence for the detection of shear arising from large-scale structure has been presented based on an analysis of 14 fields obtained at the William Herschel Telescope. Particular attention has been paid to questions of systematic correction and testing of measurement method by simulations. Prospects are now bright for measuring with greater accuracy the amplitude of the cosmic shear signal. The key uncertainties to overcome are noise and cosmic variance, i.e. more independent lines of sight will lead to a better estimate of the shear amplitude. Future cosmic shear surveys will consequently provide powerful constraints on cosmological parameters.

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